REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
09/19/2017

2. REPORT TYPE
Final Technical

3. DATES COVERED *(From - To)*
01/01/2009 – 12/31/2015

4. TITLE AND SUBTITLE
Lagrangian Studies of Lateral Mixing

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-09-1-0266

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Craig M. Lee

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Washington – Applied Physics Laboratory
4333 Brooklyn Avenue NE
Seattle, WA 98105-6613

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
875 North Randolph Street
Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT:

Distribution Statement A: Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The Lateral Mixing Experiment (LATMIX) focused on mixing and stirring at the submesocales (100 m to 10 km) in the upper ocean. LATMIX1 targeted the Sargasso Sea, southeast of the Gulf Stream, aiming for a region with relatively weak mesoscale eddy activity and clear waters to focus on submesoscale stirring by internal wave shear dispersion and finescale vorticity anomalies. LATMIX2 targeted the wintertime Gulf Stream, where deep mixed layers, strong lateral density gradients (Gulf Stream north wall) and the high probability of encountering intense atmospheric forcing provided ideal conditions for observing the generation and evolution of submesoscale instabilities. A towed profiler was used to conduct synoptic, 4D surveys to resolve submesoscale variability. Results include finding that: (i) interactions between near inertial internal waves and symmetric instability enhance dissipation at submesocale fronts, (ii) vertical vorticity in the wintertime mixed layer south of the Gulf Stream exhibits statistics, including skew, that are consistent with existing numerical predictions and (iii) Nearly flat salinity gradient spectra observed in the Sargasso Sea (taken along isopycnal surfaces) can be explained by internal wave horizontal strain at low horizontal wavenumbers, but not for shorter-scale variability.

15. SUBJECT TERMS
submesoscale dynamics, upper ocean, eddies, fronts, internal waves, mixing, stirring

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Craig M. Lee
Unclassified	Unclassified	Unclassified	UU	6	**19b. TELEPHONE NUMBER** *(include area code)* (206) 543-1300

Lagrangian Studies of Lateral Mixing

Craig M. Lee
Applied Physics Laboratory, University of Washington
1013 NE 40th St.
Seattle, WA 98105-6698
phone: (206) 685-7656 fax: (206) 543-6785 email: craig@apl.washington.edu
Grant Number: N00014-09-1-0266
http://opd.apl.washington.edu/~craig

LONG-TERM GOALS

This study contributes to long-term efforts toward understanding:

- Dynamics of sub-kilometer fronts, eddies and filaments – the oceanic submesoscale.
- The role of submesoscale physics in governing evolution of the upper ocean and its interaction with the atmosphere.

OBJECTIVES

The LATMIX2 experimental program focused on two potential mechanisms for lateral mixing:

1. Submesoscale turbulence, generated by instabilities in deep wintertime mixed layers coupled with mesoscale straining.
2. Submesoscale instabilities associated with the strong lateral density gradients of upper ocean fronts, modulated by atmospheric forcing.

Specific targets included investigating the potential role of symmetric instability in extracting energy from the mesoscale to the submesoscale, investigating the dynamics and impact of submesoscale streamers observed extending from the Gulf Stream front and seeking observational evidence of the sinuous, predominantly cyclonic, vertical vorticity field found in numerical simulations of the region southeast of the Gulf Stream's warm core.

APPROACH

Lateral stirring and mixing at the submesoscales (100 m to 10 km) play a central role in key upper ocean processes, including restratification, watermass formation and the downscale cascade of energy from the mesoscale to the dissipative scales. Accurate simulation of these processes thus relies on parameterizations of submesoscale dynamics, as most current circulation models do not resolve these small horizontal scales. This motivates efforts to advance our understanding of submesoscale upper ocean physics and develop parameterizations capable of representing their impacts in larger-scale models.

Theory and numerical simulations point to several mechanisms that may account for observed lateral mixing rates, including stirring by coherent vorticies generated by internal wave breaking, a cascade of

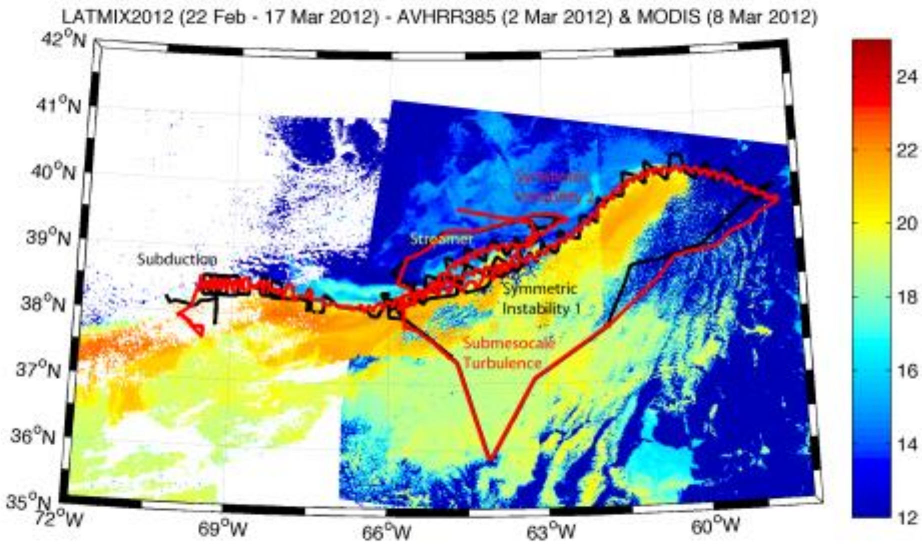

Figure 1. LATMIX2 surveys. Red (black) lines mark Knorr (Atlantis) tracks plotted over SST images from 2 separate days, corresponding to the 2 symmetric instability surveys.

tracer and potential vorticity variance produced by mesoscale straining and mixed layer instabilities, and frontal instabilities. However, the challenges associated with collecting measurements at the necessary temporal (hours) and spatial (hundreds of meters) resolution have limited the availability of appropriate observations and hindered understanding of submesoscale dynamics.

LATMIX1 (Shcherbina et al., 2015) targeted the Sargasso Sea, southeast of the Gulf Stream, aiming for a region with relatively weak mesoscale eddy activity and clear waters (to accommodate dye releases in low to moderate dispersion regimes, with airborne tracking). Observations focused on submesoscale stirring by internal wave shear dispersion and finescale vorticity anomalies.

LATMIX2 (Fig. 1) targeted the wintertime Gulf Stream, where deep mixed layers, strong lateral density gradients (Gulf Stream north wall) and the high probability of encountering intense atmospheric forcing provided ideal conditions for observing the generation and evolution of submesoscale instabilities. The close proximity of dynamically distinct environments ($Ro \ll 1$, $Ri_g \gg 1$ southeast of the Gulf Stream warm core, Ro and Ri_g O(1) at the Gulf Stream north wall) allowed for efficient investigation of submesoscale mixing resulting from mixed layer instabilities and mesoscale straining, and from frontal instabilities.

Capturing the evolution of submesoscale instabilities at the wintertime Gulf Stream front presented several severe challenges, including identifying and targeting developing instabilities, quantifying rapid temporal evolution in a highly advective environment, resolving both submesoscale dynamics and mesoscale background, and maintaining operations during periods of intense atmospheric forcing.

The LATMIX2 team developed a highly integrated approach that employed coordinated sampling by two vessels (R/V Knorr and R/V Atlantis), autonomous platforms and dye. The measurement system included:

- An acoustically tracked, turbulence measuring Lagrangian float (D'Asaro) defined a water-following reference frame. Surveys conducted in this frame resolved the time-evolution of submesoscale instabilities by minimizing advective effects.
- Repeated, submesoscale-resolving surveys of a 10km x 10km x 200m volume following the float using the Triaxus undulating, towed profiler (Lee).

- Repeated, mesoscale surveys of a 30km x 30km x 200m volume following the float with the MVP towed profiler (Klymak).
- Turbulence-measuring gliders (Shearman) sampling around the float while being carried downstream along the front.
- Fluorescein dye injections at the front (Sundermeyer) for tagging features and tracing their evolution.

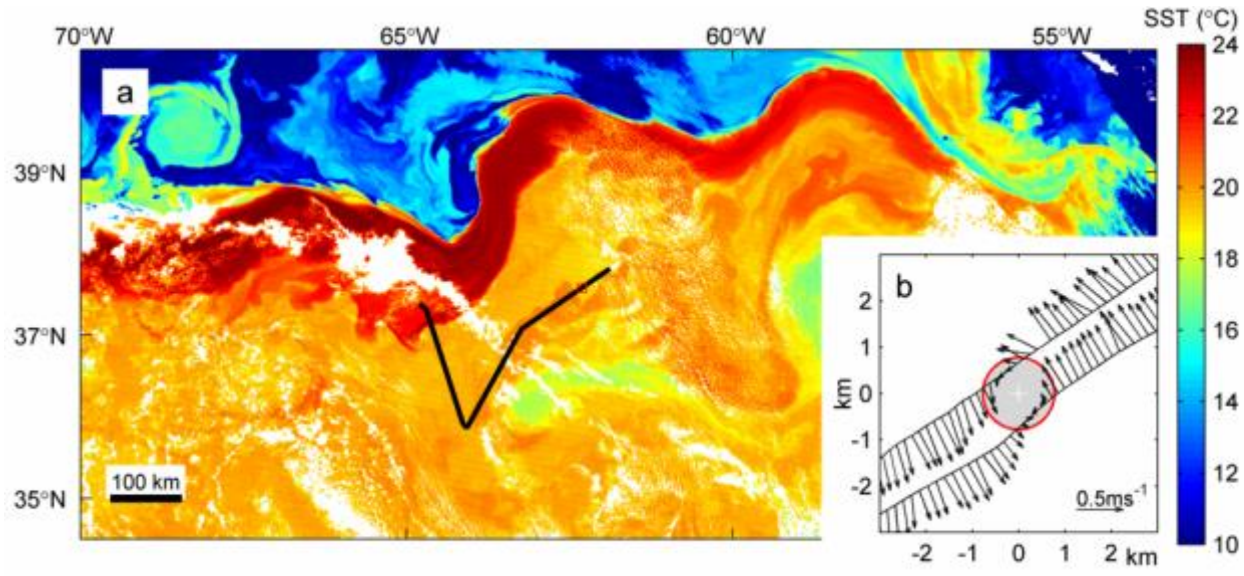

Figure 2. (from Shcherbina et al, 2013) a) Track of the synchronous survey 11−13 March 2012 superimposed on Moderate Resolution Imaging Spectroradiometer (MODIS) sea surface temperature image taken 22 March 2012. b) Enlarged fragment of the survey, showing measured near-surface velocity vectors and an example of a circle used to calculate velocity and tracer gradients. Aqua MODIS SST imagery courtesy of NASA Goddard Space Flight Center [*Feldman,* 2012]

- Theory and focused simulations (Thomas, Molemaker, McWilliams) prior to and during the field program guided experimental design and at-sea sampling decisions.

Typically, remote sensing and scouting surveys were used to target promising features. A float (and sometimes dye) was deployed into an active site (e.g. upstream of a filament formation region or at the sharpest part of the north wall front). Float-following, two-ship surveys then quantified 3D evolution over a range of scales through a multi-day drift (Fig. 1, northern tracks). An additional survey used the two ships steaming in parallel to provide unaliased estimates of 1-km vorticity, divergence and strain for an investigation of submesoscale turbulence (Fig. 1, southern excursion and Fig. 2).

Although the demands imposed by the rapid evolution and broad range of spatial scales far exceeded the capabilities of any single platform, the cooperative efforts of the LATMIX 2012 team successfully provided 4D characterizations of submesoscale dynamics in challenging operating conditions. The ability to achieve complex, difficult goals through multi-investigator teamwork is a hallmark of ONR programs.

WORK COMPLETED

LATMIX1 employed three ships (R/V Hatteras, R/V Endeavor and R/V Oceanus) conducitng coordinated operations that included dye release and nested synoptic surveys. Lee served as Chief Scientist aboard R/V Oceanus, conducting surveys to characterize mesoscale variability around the central dye release sites. Results from this effort are reported in Shcherbina et al., (2015) and Kunze et al. (2015).

The LATMIX2 measurement program employed R/V Knorr and R/V Atlantis to conduct multi-scale surveys of submesoscale features at the north wall of the Gulf Stream in winter 2012 (22 February – 16 March 2012), with Lee serving as chief scientist for R/V Knorr and as overall chief scientist for the 2012 field program. The measurement system included two towed profilers (Triaxus, aboard R/V Knorr and a Moving Vessel Profiler (MVP) aboard R/V Atlantis), Lagrangian mixed layer floats, autonomous gliders and dye injections. Two distinct float-following surveys targeted symmetric instability at the north wall front under strong wind forcing, with additional drifting surveys targeted intra-thermocline eddies and filament evolution along the north wall. A fifth effort involved an extended parallel tow (Fig. 2) in the region south of the Gulf Stream, designed to test predictions of the statistics of 1-km scale vorticity, divergence and strain derived from theories of submesoscale turbulence.

RESULTS

Symmetric instability: Two surveys executed during periods of strong, down-front winds captured symmetric instability at the Gulf Steam front. The frontal horizontal density gradient drove Ertel potential vorticity negative in the stratified surface layer at the front. Float and dye revealed energetic mixing in the negative PV region, with dye spreading indicating lateral mixing rates of ~100 m^2/s. Please see Thomas et al. (2016) for further results.

Submesoscale turbulence: The distribution of vertical vorticity in the 250-m deep wintertime mixed layer southeast of the Gulf Stream reveals significant asymmetry (Fig. 3), with strong bands of cyclonic vorticity embedded within a weak, anticyclonic background. Deep wintertime mixed layers and straining by the Gulf stream eddies likely contribute to the strong skew. Statistics within the mixed layer are consistent with numerical predictions for wintertime submesoscale turbulence in this region. Please see Shcherbona et al. (2013) for further results.

North wall filaments: Surveys along the north wall investigated streamers and instabilities thought to drive exchange across the front. Repeat sections illustrate vertical structure and evolution, and provide a rough estimate of lateral mixing.

Internal wave straining: Nearly flat salinity gradient spectra (taken along isopycnal surfaces) can be explained by internal wave horizontal strain at low horizontal wavenumbers, but not for shorter-scale variability. Please see Kunze et al. (2015) for further results.

Near-inertial mixing: Observations at the Gulf Stream front reveal ubiquitous banded shear structures with characteristics indicative of near-inertial waves guided and amplified by the front. These waves interact with symmetric instability within the mixed layer and modulate mixing in the pycnocline. Please see Whitt et al. (2017) for further results.

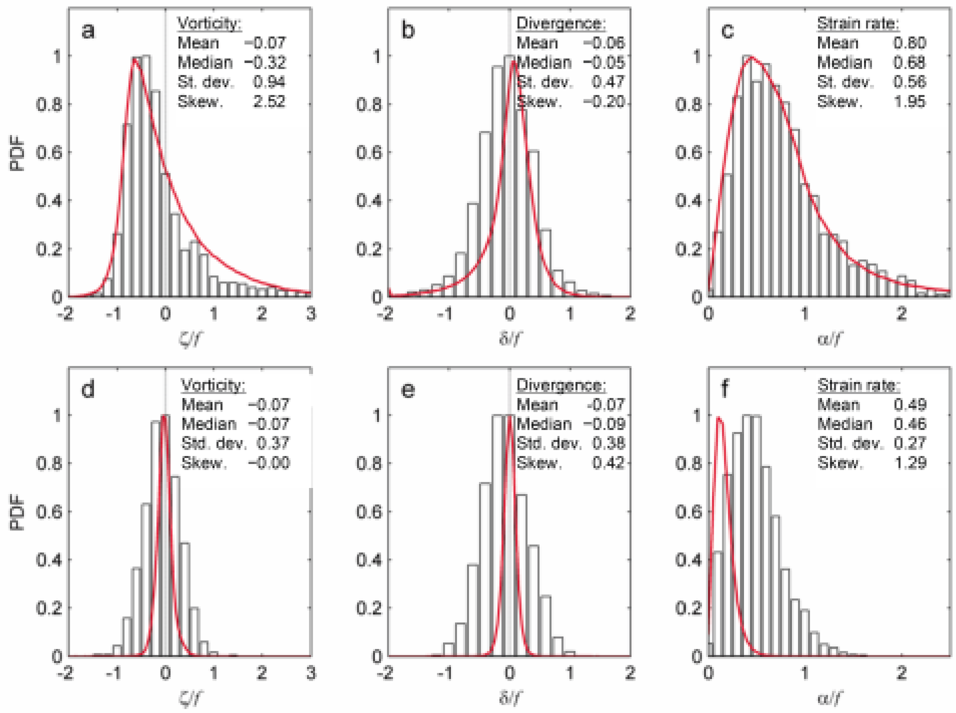

Figure 3. (from Shcherbina et. al. 2013) Histograms of normalized vorticity (left column), divergence (middle column), and strain rate (right column) in the mixed layer (0− 50m, 300kHz ADCP, top row) and upper thermocline (350-400m, 75kHz ADCP, bottom row). Red curves show corresponding distributions produced in a 0.5-km numerical model. All distributions are scaled by their maximum value. Distribution parameters are shown on the insets.

IMPACT/APPLICATION

This work builds on previous studies (e.g. Japan/East Sea subpolar front and AESOP Kuroshio Extension) aimed at improving parameterizations of sub-gridscale dynamics in numerical simulations. Ongoing work within the LATMIX team will utilize understanding gained from these observational studies to improve representation of submesoscale processes in regional models.

RELATED PROJECTS

Multiple efforts within the Office of Naval Research Lateral Mixing Program (LATMIX). This includes projects directed by principal investigators E. D'Asaro. K. Shearman, J. Klymak, M. Sundermeyer, R. Harcourt, J. McWilliams, J. Molemaker and L. Thomas.

PUBLICATIONS

* Denotes student author

Shcherbina, A. Y., E. A. D'Asaro, C. M. Lee, J. M. Klymak, M. J. Molemaker, and J. C. McWilliams (2013), Statistics of vertical vorticity, divergence, and strain in a developed submesoscale turbulence field, Geophys. Res. Lett., 40, 4706–4711, doi:10.1002/grl.50919.

Kunze, E., J.M. Klymak, R.-C. Lien, R. Ferrari, C.M. Lee, M.A. Sundermeyer and L. Goodman, 2015: Submesoscale Water-Mass Spectra in the Sargasso Sea. *Journal of Physical Oceanography*, 45, 1325-1338.

Shcherbina, A.Y., M.A. Sundermeyer, E. Kunze, E. D'Asaro, G. Badin, D. Birch, A.-M. E. G. Brunner-Suzuki, J. Callies, B.T. Kuebel Cervantes, M. Claret, B. Concannon, J. Early, R. Ferrari, L. Goodman, R.R. Harcourt, J.M. Klymak, C.M. Lee, M.-P. Lelong, , R.-C. Lien, A. Mahadevan, J.C. McWilliams, M.J. Molemaker, S. Mukherjee, J.D. Nash, T. Özgökmen, S.D. Pierce, S. Ramachandran, R.M. Samelson, T.B. Sanford, R.K. Shearman, E.D. Skyllingstad, K.S. Smith, A. Tandon, J.R. Taylor, E.A. Terray, L.N. Thomas, J.R. Ledwell, 2015: The LatMix summer campaign: Submesoscale stirring in the upper ocean. *Bulletin of the American Meteorological Society*, doi:10.1175/BAMS-D-14-00015.1.

Thomas, L.N., J.R. Taylor, E.A. D'Asaro, C.M. Lee and J.M. Klymak, 2016: Symmetric Instability, Inertial Oscillations, and Turbulence at the Gulf Stream Front. *Journal of Physical Oceanography*, 46, doi: 10.1175/JPO-D-15-0008.1.

Johnson*, L., C.M. Lee and E.A. D'Asaro, 2016: Observational Evidence of Lateral Slumping Induced Springtime Stratification. *Journal of Physical Oceanography*. doi:10.1175/JPO-D-15-0163.1.

Whitt, D.B., L.N. Thomas, J.M. Klymak, C.M. Lee and E.A. D'Asaro, 2017: Trapped super-inertial waves in the Gulf Stream, *Journal of Physical Oceanography*, in review.